STUDIES IN AERONOMY, ASTROPHYSICS AND ASTRONOMY

and

FLUCTUATIONS, NOISE AND QUANTUM ELECTRONICS

by

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SELECTED PUBLICATIONS

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PREFACE

The sixty publications selected for this thesis cover a period of forty years, from my time as a PhD student in the Physics Department of the University of Tasmania up to the present in 2002 as founding Professor of Electronic Engineering and Applied Physics and Director of the Centre for Advanced Telecommunications and Quantum Electronics at the University of Canberra.

Many of the papers have been co-authored with research students and associates whose valued contributions I have acknowledged below. Unless otherwise stated I have only included accounts of work in which I have played a leading part. I have divided the papers, in some cases somewhat arbitrarily, into two groups which reflect my interests over this period:

(a) Aeronomy, Astrophysics and Astronomy; and
(b) Fluctuations, Noise and Quantum Electronics.

Within these two groups I have attempted a further subdivision in which I have selected and presented papers to illustrate the development of specific concepts and lines of approach, usually in chronological order. This has meant the inclusion of a number of abstracts, short papers and two patent descriptions.

(a) AERONOMY, ASTROPHYSICS AND ASTRONOMY

The publications in this section cover a period of twenty seven years, starting with my PhD studies at the University of Tasmania in 1960. They include work performed at the University of Adelaide, the University of Texas at Dallas, the University of Otago and finally at the University of Canberra, prior to the commencement of my work in the field of quantum electronics and quantum optics in 1989.

My interest in transient ionizing events began with upper atmosphere radiation measurements following the high altitude thermonuclear explosion "Starfish Prime" that I made as a PhD student working under the supervision of Dr Peter Fenton. I constructed the balloon borne Geiger counter instrumentation and the telemetry system used in the measurements and analysed the data that were reported in the journal *Nature* [1]. In the following paper [2] I collated a variety of observations made at Hobart by fellow graduate student John Reid and other observers. I attempted to link these and the radiation measurements to a common cause. I concluded that there was good evidence for a breach of the geomagnetic field leading to the widespread dispersal of radioactive fission debris in both hemispheres [3,4,5], although electron precipitation from the terrestrial radiation belts could not be excluded. This view was supported in the following two decades when observations and models of the event were finally published in the open literature.

Paper [6] is an account of measurements of bremsstrahlung radiation from auroral zone electron precipitation made at Hudson's Bay as a member of a team from the University of Texas at Dallas working under the direction of Professor Ken McCracken, a graduate of the University of Tasmania. Paper [7] is an account of rocket measurements of solar x-ray and ultraviolet radiation, again made as a member of a team, in this instance from the University of Adelaide, working under the direction of Professor John Carver. I instrumented the x-ray payload and analysed the results. This work was a precursor to the launch of the first Australian scientific satellite, WRESAT 1, instrumented at the University of Adelaide and launched from Woomera.

After I moved to the University of Otago in 1968 this work stimulated my interest in deducing atmospheric parameters from solar radiation measurements [8-10]. I believe that PhD student Ms Mazlan Othman and I were among the first to suggest [8] that routine photometric observations at existing optical astronomical observatories could be utilised to monitor globally the atmospheric content of ozone and aerosols present in the atmosphere.

I subsequently convened an IAU working party and colloquium on the use of astronomical data to characterise variations in atmospheric turbidity due to volcanic eruptions.

While at the University of Otago I participated in a meteorological survey of surface wind characteristics as a member of a New Zealand Wind Energy Task Force established at the time of the first oil crisis. Two papers relating to wind energy generation and site characterisation are listed here [11,12]. The first of these was co-authored with my colleague and co-director Mr Keith Dawber, with whom I shared the planning and execution of a regional wind energy survey of the South Island of New Zealand. My monograph on wind power economics and technology and three co-authored formal reports published by the New Zealand Energy Research and Development Committee have not been included here. In the intervening 25 years wind power has become economically viable. Extensive wind energy farms have been selected and established worldwide on the basis of principles established in the New Zealand survey and other regional surveys. Further publications arising from this work relating to stochastic phenomena are listed below [33-36].

Before moving from the University of Adelaide to the University of Otago in 1968 I participated in auroral zone [6] x-ray measurements from balloon borne platforms in Canada, and astronomical x-ray measurements [13,14,15] from balloon borne platforms in the USA and Australia under the direction of Professor Ken McCracken.

I also performed theoretical modeling studies relevant to the interpretation of astronomical X-ray observations. In particular I devised models for transient celestial x-ray sources [16,17] that were then being observed for the first time. The first of these [16] was written in collaboration with PhD student John Harries. In two later papers written in New Zealand [18,19], I addressed the possible contribution made by a class of young active red dwarf stars known as "flare stars" towards (a) the diffuse galactic x-ray background and (b) the galactic cosmic ray background particle flux, the latter in collaboration with PhD student Malcolm McQueen. I showed that flare stars were unlikely to make significant contributions to the x-ray background. We also demonstrated that the flare star contribution to the galactic cosmic ray flux density was negligible, contrary to several long-standing suggestions in the literature. These conclusions have since been confirmed. In 1971 I was awarded the Murray Geddes Prize for astronomical research by the Royal Astronomical Society of New Zealand.

While at the University of Adelaide I had became interested in the possibility of detecting stellar x-rays from the ground based on my earlier work on ionising radiation in Tasmania and the USA [1-6]. At that time x-ray astronomical satellites were not yet in orbit and observations were only possible from rocket and balloon platforms. Following my arrival in New Zealand, I made contact with Mr Godfrey Burtt and Mr Fred Knox of the ionospheric section of the New Zealand Department of Scientific and Industrial Research with a view to searching their VLF radio propagation records for evidence of ionospheric effects caused by the x-radiation from celestial sources, similar to those due to solar flares, first documented by Professor Ronald Bracewell while studying at Cambridge.

We discovered and published the first evidence for an extra-solar x-ray influence on the terrestrial ionosphere in 1969 [20,21]. This stimulated a lively debate in the ionospheric literature and the reality of the effects was initially questioned on both theoretical and observational grounds. Following additional observation, extensive analysis and review, the ionospheric perturbations due to the celestial x-ray source Scorpius XR1 were confirmed to be significant, although somewhat smaller than we had initially reported. On this basis I was able to set conservative upper limits [22,23] to the prompt x-ray flux from the large supernova SN1987a. This provided early support for the pre-explosion blue dwarf stellar model of SN1987a which was finally adopted.

On the strength of this work I suggested that large non-solar x-ray and gamma ray bursts would be detectable by global networks of VLF radio receiving networks [24]. However, positive observations of large ionospheric effects due to transient galactic x-ray bursts did not take place until 1998. Unambiguous measurements of the effects of a large gamma ray burst on the nocturnal Pacific ionosphere were then made with networks designed to detect electron precipitation events by Professor Richard Dowden of the University of Otago and Professor Umran Inan of Stanford University.

I was invited to present a review of these two sets of observations at the 26th General Assembly of URSI held at Toronto in 1999 [25]. A comprehensive review is in preparation but is not included in this thesis.

(b) FLUCTUATIONS, NOISE AND QUANTUM ELECTRONICS

The papers in this section have a common theme: the analysis of physical systems and processes in which random and chaotic fluctuations play an important part.

I wrote the first paper [26] while a PhD student in the Physics Department at the University of Tasmania engaged in the radio telemetry of cosmic ray data from balloons. I believe it was the first attempt to optimise the choice of bearer frequency for terrestrial VHF radio links taking galactic and other radio noise sources into account.

The second paper [27] was co-authored with graduate student Robert Hurst who performed the measurements under my supervision as part of a physics honours project at the University of Otago. It confirmed our expectation (based on the central limit theorem) that the narrow-band rectified electrical noise after low pass filtering would follow Gaussian statistics, contrary to assertions in at least one contemporary monograph on radio astronomy.

The following five papers [28-32] describe an investigation I initiated into the use of cross-correlation techniques to detect weak time-variations of physical interest in the presence of masking noise. This work was performed with the assistance of graduate students Robert Hurst, Malcolm McQueen, Grant Christie, Graham Stanley and research associates William Allen and Mervyn Thomas who were engaged in projects in the fields of radio astronomy, optical astronomy and night-sky photometry under my leadership.

The application of these techniques in these fields was considered innovative at the time of publication but has now become common practice. Paper [32] is of particular interest in that it provided an early indication of the importance of low level electron atmospheric precipitation from the radiation belts in maintaining the mid latitude ionosphere. This issue also arose in connection with my earlier discovery (with Burtt and Knox [20,21]) of weak ionospheric perturbations due to celestial x-ray sources.

Paper [33] is a short mathematical analysis of the unexpected and (until recently) unexplained power law character of horizontal wind speed gust durations discovered during the course of a survey of surface winds in New Zealand [11,12]. In this paper I also drew attention to the apparent ubiquity of the power law characteristic. At that time fractal analysis was in its infancy and level crossing statistics were usually regarded as being in the "too hard" box. In 1989 I noted [34] an interesting application of zero-crossing interval analysis in the field of spectral estimation that I later confirmed while on study leave at the CSIRO Division of Radiophysics working with Dr Warwick Wilson.

After a lapse of 20 years I revisited level-crossing phenomena in an invited presentation to a 1999 conference on "Unsolved Problems of Noise" [35], suggesting that a reanalysis of the data from a fractal viewpoint might be fruitful. I was subsequently invited to prepare a paper along these lines for publication in the journal *Chaos*. My former student and colleague Dr Robert Hurst had played a major role in identifying the wind characteristics in the original New Zealand wind energy survey. He kindly agreed to assist me in preparing the invited paper [36] by reanalysing and modelling some of the original data logged on magnetic tape that he was able to access in New Zealand. Largely as a result of his endeavours we were able to confirm the fractal characteristics of the horizontal wind field and to successfully simulate these to a good approximation by a Markov process. Although originally conceived in the context of aero-generator performance, this analysis also appears to have other unexpected practical applications, for example to the dynamics of bushfires.

On a more fundamental level it should help to clarify the connection between the properties of continuous-time stochastic processes and the fractal statistics of the point process generated by their level crossings.

Following my return to Australia from New Zealand in 1982 I became interested in the fields of non-classical "quantum" optics and electronics in which the quantum character of light is accessible through measurements of photon counting noise and photo-current shot noise fluctuations. I attended a seminar at the Australian National University in 1989 in which I heard that NTT researcher Dr Yoshihisa Yamamoto had recently demonstrated photonic shot noise reduction (and by implication sub-Possonian photon counting statistics) using cooled semiconductor lasers.

I subsequently succeeded in performing the first Australian (and the second international) demonstration of photonic noise reduction using light-emitting semiconductor junction diodes [37]. I also confirmed for the first time the non-classical statistics of the emitted photons by showing that the maximum fractional shot noise reduction closely tracked the quantum counting efficiency as this latter quantity was varied [37-39]. In the latter paper, published in the *Physical Review Letters*, I also demonstrated for the first time the generation of correlated photon "twin beams" using semiconductor light emitters [39]. Co-author Professor Graham Pollard was responsible for an important link equation (6) in the theoretical development in this paper. He also generalised (to N beams) the equations for the conditional single-photon multiplet source derived from this concept in a later publication [60].

In 1993 I published a semi-classical interpretation of the high-impedance suppression of shot noise in light-emitting diodes [40]. More detailed models proposed by the Yamamoto group at Stanford and the Yamanishi group at Hiroshima University incorporating the dynamics of the injection process have since been shown to be superior [58]. However, this "leaky reservoir" model remains a satisfactory first-order model of shot noise reduction under conditions of high charge-carrier injection in semiconductor junctions.

My work on quantum noise suppression in light-emitting diodes has been incorporated into undergraduate physics and engineering courses at the University of Canberra and Macquarie University [41]. When working on sabbatical leave at the UK Defence Research Agency with Professor John Rarity I coined the words "quiet light" to describe the character of quantum intensity noise-suppressed light. My work on quiet light was featured in the New Scientist (June 28 1997, Forum p47). Professor Rodney Tucker, winner of an Australia Prize for his work on laser modelling, wrote the following generous comment in assessing my 1992 research grant application in this field.

"The importance of this work was highlighted to me when I recently attended the international conference on lasers and electro-optics in California. There was a keynote invited address by Dr Yamamoto from NTT, the recognised world leader in the area of "squeezed light". In his keynote address, Dr Yamamoto referred to only one other researcher apart from those in his own group. This other researcher was Professor Edwards. This clearly indicates the high international esteem and reputation that Professor Edwards has received for his work in this area".

In 1991 after spending sabbatical leave at the NTT laboratories in Tokyo as the guest of Dr Yamamoto, I presented a paper in Vienna in which I reported for the first time the generation of positively (and negatively) correlated quantum noise fluctuations in photon "twin-beams" achieved by electrically connecting two light-emitting diodes in series (or parallel). As stated above, this was subsequently published in the *Physical Review Letters* [39] and was later patented [42]. Up to this time the only method used to generate correlated light beams involved parametric down conversion in non-linear optical media. It then occurred to me that if the light from a series-connected array of laser or light-emitting diodes could be efficiently collected and detected, a quantum noise-suppressed optoelectronic "photon-number amplifier" could be implemented. This concept was reported in the *Electronic Letters* [43] and was selected by the Optical Society of America as a principal advance in the field of quantum optics in 1993 [44].

I developed the concept of "wired" optics further at an invited plenary paper presented to an international quantum optics meeting in Rotorua [45]. In 1995, in collaboration with Dr Yong-qing Li and other members of my research group I was able to demonstrate for the first time [46] the generation of quantum-correlated twin beams using laser diodes provided by Professor Yamamoto at Stanford University.

An investigation of the second order statistics characterising the correlated fluctuations in twin-beam sources of this kind was reported in [47]. This showed that certain classical inequalities were violated in a manner that unambiguously revealed the quantum (non-classical) character of infrared and visible light fields, even in the macroscopic case. This work was carried out jointly with Dr Y-q Li and Dr Huang Xu. It showed that these non-classical characteristics were not restricted to weak fields as had often been assumed. Dr Li later co-authored a formal quantum mechanical interpretation of our joint work on correlated shot noise from semiconductor twin–beam sources [48]. At the suggestion of Dr Xiao of the University of Arkansas, Dr Li and Dr Peter Lynam demonstrated the use of amplitude-squeezed light in improving the quality of light-wave based measurements [49]. Through illness during 1996/8 I was unable to participate directly in this experimental work. However I made a major contribution to the analytic interpretation and wrote the text of the paper that subsequently appeared in the *Physical Review Letters* [49].

My earlier work on shot noise-suppressed photon number amplification [42-45] enabled me to achieve a better understanding of the origin of shot noise in electronic and photonic devices. This work formed the basis of several conference presentations, journal publications and an invited book chapter in a monograph on noise in electronic devices [55-58]. It also led to a second invention that became the subject of Australian, Japanese and US patents [42,51].

This invention was based on the application of positive feedback to the open loop amplifier of [43] to achieve increased current gain [50]. This concept was embodied in international patents [51] in which my colleague Dr William Cheung and I were cited as co-inventors. We subsequently carried out a detailed shot noise analysis of the closed loop optoelectronic photon-coupled amplifier [52] and this was incorporated into the final version of the patent specifications. Dr Y. Mizushima and colleagues at Hamamatsu Photonics facilitated this work which was featured in the journal *Laser World Focus* in 1997.

I subsequently realised that the closed loop configuration was similar to (but more general than) that of a "photon-coupled transistor" and that the phenomenology of noise suppression in photonic devices had an exact analogue in semiconductor junction transistors. This led me to develop a successful "neo-corpuscular" model of shot noise generation, propagation and suppression in electronic and photonic devices [55-58] based on the original work of Aldert van der Ziel in the 1950s. In 1999 I presented an invited paper [56] co-authored with graduate student Richard McDonald and co-supervisor Dr Cheung that applied this model to a bipolar junction transistor.

With the assistance of Professor Yamamoto and members of the semiconductor device development group at Hamamatsu Photonics we succeeded in 2000 in demonstrating for the first time the operation of a photon-coupled transistor employing a quantum noise suppressed laser, the exact photonic analogue of a bipolar junction transistor [54].

In 2001 I was invited to write a chapter on sub-Poissonian electronic and photonic noise in semiconductor junctions for a monograph on noise in electronic devices. This reviews several decades of work on the suppression of quantum noise in light-emitting junctions [58], including work on light-emitting diodes with ME student Ting-ting Zhang [55]. Paper [53] describes work on the characterisation of light-emitting diodes performed with colleagues Dr Graham French and Dr Cheung.

My most recent work in the field of quantum fluctuations has been an investigation of quantum cryptographic techniques. I initiated, supervised and helped implement the first demonstrations of quantum key distribution in Australia [59]. In 2001 I gave an invited presentation of this work and a related analysis of a conditional single-photon source [60] based on original concepts introduced in [42-46] at an international workshop held in Corsica.

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I acknowledge with thanks the invaluable guidance and assistance of the academic colleagues, graduate students and research assistants, particularly those named above, with whom I shared the excitement and the frustrations of the research ventures sketched in this thesis. In the preface I have attempted to acknowledge specific contributions to the work reported here. I apologise for the inevitable inadvertent omissions.

Paul J Edwards 10-09-02

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